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Assessment of CCHP systems based on biomass combustion for small-scale applications through a review of the technology and analysis of energy efficiency parameters

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HIGHLIGHTS

- Assessment of biomass CCHP systems based on prime movers and chillers integration.
- Scarcity of commercial prime mover units limits small-scale CCHP plants.
- Low temperature ORC can be integrated in CCHP plants in an energy efficient way.
- Integration of SE and ADS entail wider ranges of cooling-to-heating ratio.
- Unit direct coupling is more important to achieve PES than higher efficiencies.

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ABSTRACT

An alternative way of increasing and improving the use of biomass resources and distributed generation is by using combined cooling, heating, and power (CCHP) small-scale plants. The first step in designing a CCHP plant is to determine the best configuration in terms of the thermodynamic integration of all the subsystems and the optimization of the overall energy efficiency.

In this work, small-scale biomass CCHP systems are evaluated to provide a basis for studies on their thermodynamic feasibility and energy efficiency in two main sections. First of all, a state of the art review is presented regarding the technologies involved in CCHP systems based on biomass combustion. The conclusion drawn might initially be considered obvious: the best prime mover (PM) technology to develop this type of plant is the Stirling engine (SE) due to its higher electric efficiency, but its low market availability and operational problems currently limit its use in commercial plants. The organic Rankine cycle (ORC) is a very widespread technology but its use in CCHP systems in the power range between 1 and 200 kW_e is limited due to their low sink temperatures, which prevent its direct cascade integration with thermally activated cooling (TAC) for refrigeration. However, it is possible to integrate these technologies in an energy efficient way (achieving primary energy savings) if the plant is designed according to some guidelines regarding the heating and cooling production. The second section of this work demonstrates this idea by analyzing different possible integrations of the prime movers and TAC units currently available on the market. The overall performance and the energy feasibility, in terms of the relation between the heating and cooling loads, are evaluated through a parameter analysis, using the Artificial Thermal Efficiency (ATE) and the Primary Energy Saving Ratio (PESR). The evaluation of the configurations proposed shows that direct coupling of the PM and TAC units is highly important, more so than high efficiency and coefficient of performance (COP) of the technologies, for achieving primary energy savings in almost every possible relation between the cooling and heating loads generated by the CCHP plant. As a result, some guidelines are proposed to develop small-scale CCHP plants based on biomass combustion in an energy efficient way.

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Nomenclature

ATCS	annual total cost savings (%)
ATE	Artificial Thermal Efficiency (%)
C	cooling factor (dimensionless)
COP	coefficient of performance (dimensionless)
$\dot{F}$	fuel (kW)
PESR	Primary Energy Saving Ratio (%)
$\dot{Q}$	heat rate (kW)
RefH	reference boiler efficiency (%)
RefE	reference power plant efficiency (%)
Ref_{COP}	reference chiller coefficient of performance (dimensionless)
T	temperature (°C)
$\dot{W}$	power (kW)

Greek letters

Δ	difference (–)
η	efficiency (%)

Subscripts

act	activation
e	electric
extra	extra
high *T*	high temperature
low *T*	low temperature
min	minimum
PM	prime mover
rej	rejection
TAC	thermally activated cooling
th	thermal

Abbreviations

ABS	absorption cooling
ADS	adsorption cooling
CCHP	combined cooling heating and power
CHP	combined heating and power
n/a	not available
O&M	operation and maintenance
ORC	organic Rankine cycle
PM	prime mover
SE	Stirling engine
TAC	thermally activated cooling
PES	primary energy savings

1. Introduction and objectives

Combined cooling, heating, and power (CCHP) systems are mainly based on the integration of a combined heat and power (CHP) module, also known as a prime mover, which generates electricity and heat, and a thermally driven chiller which produces a cooling effect. These systems lead to higher global efficiencies in comparison with stand-alone generation in large power plants; they also allow primary energy savings and emission reduction and enhance the reliability of the supply network [1–4].

Fossil-fuelled CCHP plants are widespread, so they are the technologies involved. Also, renewable resources (e.g. solar thermal or biomass) and waste heat recovery may be considered to substitute non-renewable based systems, but these types of plants are at an early stage of development, along with some of the technologies involved [5].

Recent progress in biomass fuelled CCHP systems is associated with decentralized generation, where the final energy systems are located not far from biomass sources and end user facilities, reducing problems related to their complex supply chain [6].

Among solid biomass thermochemical conversion processes, combustion is the most advanced and market-proven one, while pyrolysis and gasification can still be considered to be at a pre-commercial stage of development.

The present work is focused on the integration of biomass combustion systems with the power and cooling generation units available in the market. Some of these technologies present operational problems that penalize reliability and efficiency and partially slow down their market penetration. However, it is currently possible to integrate them in small-scale CCHP systems to meet different energy demands (such as thermal demands for space heating and cooling or domestic hot water) and to achieve primary energy savings in the process. This work reflects this idea through two main parts.

In the state of the art section both prime movers and cooling technologies suitable for their integration in a bio-fuelled CCHP system are reviewed, including demonstration projects, main manufacturers, developing trends, and a summary of the main characteristics. These technologies are the *organic Rankine cycle* and the *Stirling engine* for power generation and *absorption* and *adsorption* chillers for cooling production. This review is essential to consider their possible integration in CCHP plants based on biomass combustion.

The average technical characteristics of the technologies reviewed are taken into consideration when modeling the coupling of prime movers and thermally driven chillers, in order to generate, from biomass combustion, power, cooling, and low grade heating. The integration of these subsystems is assessed through a parameter analysis, taking into consideration the primary energy savings in comparison to stand-alone generation plants.

In summary, the aim of this paper is to assess the possibility of developing small-scale CCHP systems based on solid biomass combustion using the currently available technology in an energy efficient way.

2. State of the art and development of CCHP technologies

This section presents a review of the equipment which at present might integrate solid biomass fuelled CCHP systems, divided into prime movers and thermally driven chillers, focusing on the developing status and trends, applications, and main technical barriers that currently limit the widespread use of this technology.

2.1. Prime movers

Organic Rankine cycles (ORCs) and Stirling engines (SEs) are two promising and innovative technologies which are of great interest for biomass CHP plants up to 2 MW_e [7]. In the power range from approximately 200 kW_e to 2 MW_e the ORC process has demonstrated its technological maturity. For smaller power applications SEs are now the most suitable technology to meet the requirements of this market segment [8]. A summary of the average performance characteristics and costs of both prime movers is shown in Table 1. It is important to notice that these prime movers are emerging technologies, therefore, prices vary widely and tests results are not always published.

Table 1
Summary of prime movers' average performance characteristics ([7,39–41] and commercial units' technical documentation).

	SE	ORC
Heat source	Direct fired (gas, biomass), solar radiation	Direct fired, thermal oil, overheated water (biomass, solar thermal, geothermal, waste heat)
Power range (kW_e)	1–150	3–2000
Electrical efficiency (%)	15–35	8–23
Global efficiency (%)	65–85	60–80
Heat source temperature (°C)	650–1100	90–400
Cooling temperature (°C)[a]	20–80	
Working fluids	Helium, hydrogen, nitrogen	R-245fa, R-134a, R-152a, n-pentane, toluene, siloxanes
Performance characteristics	Fast response, quiet operation, good performance at partial loads	Reliability, availability, low grade heat operation
Specific investment cost (€/kW_e)	5000–14,000	1000–6000
O&M costs (€/kW h)	n/a	0.003–0.009

[a] Cooling temperatures vary widely depending on the use mode: CHP or electricity generation only.

2.1.1. Stirling engines (SEs)

SEs achieve quiet operation and good partial load performance, so they are suitable for applications in residential, commercial, and institutional buildings.

There are not many commercial SE units and most of them are driven by natural gas, biogas, or even solar parabolic concentrators. Biomass-fuelled SEs have reached the demonstration stage but only a few market proven units are available yet (low ash content fuels). Ash from some solid biofuels might melt when burned, leading to fouling and slagging problems. As a result, heat transfer in combustion systems and heat exchangers is penalized. The temperature in flue gases must be high in order to achieve acceptable specific power and efficiency and, at the same time, problems with fouling have to be minimized so as to extend maintenance intervals [9,10].

Several projects have studied the performance of biofuelled SEs in the last two decades. All of them have designed, implemented, and put into operation pilot plants with different small-scale SE units based on biomass combustion [11–17].

Some companies have developed solid biomass fired SE prototypes. In the last years, KWB GmbH in Austria and Sunmachine GmbH in Germany tried to commercialize micro-scale CHP units (1 and 3 kW_e respectively) and even launched a few series but they ceased production due to their final high specific cost and operation and maintenance problems. Currently, the most well-known company in this market sector is Stirling DK in Denmark, which manufactures 35 kW_e SEs, which are suitable for operation with flue gases with low particles or ash content. Also, the introduction of wood pellet fired units from some other companies such as Öko-FEN Research and Development GesmbH in Austria is expected in the near future.

SEs have large potential in small-scale CCHP systems since they present high efficiencies; in theory, they can reach the Carnot efficiency due to the internally reversible nature of the process involved in the Stirling cycle [18]. Also, some SE units are designed to work as CHP units (as they have high sink temperatures that allow the use of the rejected heat), so their possible integration in CCHP plants is obvious. However, high investment costs and lack of proven operation and durability are the main obstacles to their commercialization. In fact, significant work is needed to reach a higher level of development (lower investment costs) to successfully compete with other technologies and enable their commercial use.

2.1.2. Organic Rankine cycle (ORC)

Organic Rankine cycle is considered to be a promising alternative for electricity production in plants of smaller size than those attainable by traditional steam power plants. Biomass fired, geothermal, and heat recovery plants are its typical fields of application [19].

Most bio-fuelled ORC plants are located near to biomass production sites and where great heat demands exist, such as near wood processing industries (mainly sawmills), biomass drying plants, pellet producers, district heating systems [20–24]. At present, more than 140 biomass fired ORC-plants have been installed all over Central Europe [25], as it is the most well-proven and commercially available technology for decentralized cogeneration based on biomass combustion [26].

The main targets of the current demonstration plants are related to further developments in both process coupling and organic fluids to match the temperature of the available heat. A high level of process control and automation is necessary to ensure a stable heat input to the system and to attain efficient operation [27–32]. Regarding small-scale ORC, further research must be directed towards enhancing higher electric efficiencies without forgetting cost reduction to allow market penetration [33–37].

Some manufacturers commercializing ORC modules in the approximate range between 200 kW_e and 2 MW_e are Adoratec GmbH, Barber Nichols Inc., Cryostar, GMK, Opcon AB, Ormat Technologies Inc., Pratt & Whitney, TransPacific Energy Inc., Turboden, and WOW Energies.

For small power applications, the ORC process is still in the development and early commercial stages since economies of scale penalize both the efficiency and the specific cost of these units [38]. However, some manufacturers such as ADATURB GmbH, Bosch KWK Systeme GmbH, ElectraTherm, Rank, Eneftech Innovation SA, Freepower, Genlec, Infinity Turbine LLC, Tri-O-Gen B.V., and Turbolina GmbH & Co. Ltd., among others, provide ORC modules with net power outputs below 200 kW_e.

It is important to note the difference between these two main groups of ORC units. On one hand, the higher power modules operate with working fluids (n-pentane, toluene, siloxanes) with higher evaporation temperatures which give both higher efficiencies and also the ability to condense at temperatures that enable the use of the rejected heat (>60 °C). On the other hand, up to 200 kW_e (or even 250 kW_e in some modules) the units usually use low boiling point hydrocarbons (R-134a, R-245fa, R-152a) as working fluids, which give lower efficiencies (8%–15%) and lower heat sink temperatures (~25 °C) that limit the subsequent use of the rejected heat. In summary, it is obvious that high temperature ORCs (ORC_{highT}) present a higher potential for integration in CCHP plants, as prime movers, than low temperature ORCs (ORC_{lowT}), which are more suitable for use as bottoming cycles.

2.2. Thermally activated cooling (TAC)

Absorption and adsorption chillers are thermally driven technologies which are widely applied in existing CCHP systems. They can use waste heat from prime movers to deliver cooling, enabling better and longer exploitation of the whole system and attaining higher plant efficiency and lower emissions in comparison to stand-alone generation [42].

TAC units allow the use of different heat sources for cooling generation, such as direct heat from combustion (NG, LPG, propane, diesel, etc.), exhaust or waste heat from prime movers, waste heat from industrial processes, or solar thermal, geothermal, or biomass energy. These types of heat sources present a wide variation in temperature levels and flow rates, so the key point when considering taking advantage of TAC systems lies in the optimum integration of the systems for energy cascade utilization.

2.2.1. Absorption

Absorption chillers are the most widely used TAC units in existing CCHP systems. There are two commonly used absorbent–refrigerant working pairs: water–lithium bromide, typically adopted for air conditioning applications, and ammonia–water, suitable for large size industrial applications and also for small cooling capacities in dwellings. Table 2 summarizes the characteristics and costs of commercial absorption chillers.

There are many manufacturers and distributors of this cooling technology all over the world. Suppliers of large cooling capacity lithium bromide–water absorption chillers (from 100 kW_{th}) are Broad Air Conditioning Co. Ltd., Carrier-Sanyo, Century, Ebara, Entropie, Hitachi Appliances Inc., Kawasaki Thermal Engineering (KTE), LS Mtron Ltd., McQuay, Shuangliang Eco-Energy, Thermax Ltd., Trane, World Energy Co. Ltd., Yazaki, and York-Johnson Controls. In the last few years small power units have been produced by EAW Energieanlagenbau GmbH, Rotartica (stopped production in 2010), Sonnenklima (prototype), and Yazaki. Water–ammonia absorption chillers are suitable for industrial and process refrigeration, since they provide lower chilled water temperatures. Manufacturers supplying units from 100 kW_{th} are Apina, Carrier, Colibri bv, Energy Concepts Co. LLC, Mattes Engineering GmbH, and Thermax Ltd. Small capacity products and prototypes have been available on the market only for the last few years and are being developed by Ago AG, Cooling Technologies Inc., Energy Concepts Co. LLC, Pink GmbH, and Robur.

Experiences and literature concerning cooling production with absorption technology linked to biomass combustion are based on water or steam driven chillers [17,32,43–46] or even on hot air as the heat source [47], but rarely on direct fired units. Integration of absorption chillers with prime movers such as gas turbines or internal combustion engines is an emerging technology [48–51]. On the contrary, only one known experience has tested the application of direct fired small-scale systems with biomass resources, which was carried out by the company Yazaki [52], and the authors are unaware of their testing with high ash content fuels, which might entail significant long-term operation problems.

2.2.2. Adsorption

Adsorption cooling is a novel technology which is environmentally friendly and effective in the use of low grade heat sources [1]. Compared to other thermally activated cooling systems, adsorption chillers offer the significant advantage that they can be driven by lower temperature heat sources. Nevertheless, lower coefficient of performance (COP) and higher specific investment costs have slowed down a broader application of this technology. Active research regarding adsorption chillers is being carried out in many countries [1].

Commercial adsorption units are available in capacities of up to a few megawatts. Main suppliers are InvenSor GmbH, Mayekawa Co. Ltd. (Mycom), Nishiyodo, Power Partners Inc. (ECO-MAX), SorTech AG, and Weatherite Manufacturing Ltd. Average characteristics and costs of adsorption chillers are listed in Table 3.

Since the heat source temperature level is lower than that in absorption chillers, the commercialized units are hot water driven. At present, experimental studies have analyzed adsorption chillers powered by waste heat exhausted from engines, generally for ice making and air-conditioning purposes in mobile applications [55–57]. These studies where carried out using fossil fuels but not biomass flue gases, as occurs with absorption chillers.

2.3. Integration of prime mover and TAC units in CCHP plants

Once the ORC, SE, and absorption and adsorption refrigeration technologies have been reviewed, it is possible to assess their integration in CCHP plants based on biomass combustion according to their technical characteristics regarding electrical efficiency and nominal operation temperatures.

The ideal plant configuration, whatever the technologies that it might include, has to be based on the cascade utilization of energy, which is the direct coupling of a prime mover heat sink and a TAC unit heat source. So, the heat rejected from the prime mover can be used to drive the cooling unit and the heating applications. Unfortunately, this direct coupling is not always possible in terms of thermodynamics due to the higher temperature of the cooling unit

Table 2
Characteristics of commercial absorption technologies ([1,41,53,54] and commercial units' technical documentation).

System	Ammonia–water		Water–Lithium Bromide			
	Single effect		Single effect	Double effect		
Heat source	Hot water/steam	Direct fired	Hot water/steam	Hot water/steam	Exhaust	Direct fired
Cooling capacity (kW_{th})	9–3500	17–2500	15–7000	230–20,000	230–11,630	70–11,630
COP	0.5–0.7	0.68	0.6–0.75	1.2–1.45	1.41	1–1.43
Chilled water temperature (°C)	(−50)–0[a]6–12[b]			5–10		
Heat driving circuit temperature (°C)	80–115	–	80–180 Saturated steam (1–3 bar)	<200 Saturated steam (< 8 bar)	300–600	–
Cooling temperature (°C)	25–30 (water)	15–50 (air)		25–35		
Performance characteristics	Low temperatures, environmentally friendly working fluids, air cooling, small size		Relatively low investment cost, high COP, non-toxic or inflammable working fluids, low working			
Investment cost (€/kW_{th})	400–1500	300–600	400–900			
O&M cost (€/kW h)[c]	0.002–0.006		0.001–0.006			

[a] Industrial cooling applications.
[b] Air conditioning applications.
[c] These costs are not referred to operation with biomass.

Table 3
Characteristics of commercial adsorption chillers ([53] and commercial units' technical documentation).

Working pair	Cooling capacity (kW_{th})	COP	Chilled water temperature (°C)	Cooling water temperature (°C)	Hot water temperature (°C)	Investment cost (€/kW)	O&M cost (€/kW h)
Silica gel–water	5–1700	0.56–0.6	6–12	27–29	32–90	500–1700	0.002–0.006
Zeolite–water	3–430	0.55–0.69	10–15		45–100		

heat source (typically 60–90 °C) in comparison to the prime mover heat sink. This is the case of small-scale ORC, which has a heat sink temperature between 20 and 35 °C, while in ORCs with net power outputs higher than 200 kW_e, and in SEs, the heat sink temperature varies from 20–35 °C (power generation) to 60–80 °C (CHP) depending on its use. However, it is possible to integrate them in an energy efficient way, which is achieving primary energy savings in comparison to stand-alone conventional plants. So, in order to integrate these technologies in CCHP plants, the prime mover cooling flow might increase its temperature to drive the refrigeration unit and the heating, and such an increase can be achieved by the use of biomass flue gases exhausted from the same burner that also provided the prime mover heat source.

According to operational experiences from existing plants, the integration of ORC_{highT} and SE in CCHP systems entails primary energy savings. It is also known that the use of SE allows the highest primary energy savings to be attained due to its higher electrical efficiency. So, the aim of this work is to compare the performance of ORC_{lowT} and the rest of the prime movers when they are integrated with TAC units in these types of plants. This comparison is presented in the following section in order to draw conclusions about its possible current application to the development of efficient systems in comparison to stand-alone generation and existing CCHP plants based on biomass combustion with SE or ORC_{highT}.

3. CCHP model

This section describes the general thermodynamic model for developing the energy efficiency parameter analysis, which will conclude with steady-state design specifications to achieve primary energy savings in small-scale CCHP plants based on biomass combustion. A schematic view of the overall system, representing a general integration of all possible subsystems, is shown in Fig. 1. It consists of a basic prime mover (ORC or SE) and a thermally driven chiller (adsorption or absorption), which are considered to be respectively fuelled by the flue gases from a biomass burner and by hot water.

3.1. CCHP model description

As can be seen in Fig. 1, biomass ($\dot{F}$) feeds the burner to generate heat rate from its combustion ($\dot{Q}_{burner}$). Since the aim of the model is to include every possible case, with regard to the technologies involved and different cooling-to-heating ratios, it reflects two main different distributions of the heat rate produced in the burner. On the one hand, ($\dot{Q}_{burner}$) can be entirely used to drive the prime mover ($\dot{Q}_{burner} = \dot{Q}_{act,PM}$). This case occurs when the heat rate rejected from the prime mover ($\dot{Q}_{rej,PM}$) has a higher temperature level than the one required by the chiller, so, the PM cooling flow can drive the TAC unit to produce $\dot{Q}_{cooling}$. On the other hand, there might be a case when the nominal heat source temperature of the TAC is higher than that from the rejected heat. Then, extra heat from the burner ($\dot{Q}_{extra}$) is required to raise the temperature of the PM cooling flow to properly drive the chiller within its nominal operation characteristics.

Depending on the plant cooling-to-heating ratio, $\dot{Q}_{rej,PM}$ (and $\dot{Q}_{extra}$, depending on the case) is also used to supply low temperature heating ($\dot{Q}_{heating}$). Also, heat losses ($\dot{Q}_{loss}$) are taken into account when the heat rate rejected by the prime mover is not used to generate cooling or heating.

According to this description, the thermodynamic model that describes the system proposed in Fig. 1 is summarized below[1].

The power produced by the prime mover can be determined as

$$\dot{W} = \dot{Q}_{act,PM} \cdot \eta_{PM} \quad (1)$$

where η_{PM} is the electric efficiency of the prime mover. The heat rate supplied by the flue gases from biomass combustion is estimated, neglecting heat losses, as

$$\dot{Q}_{act,PM} = \dot{W} + \dot{Q}_{rej,PM} \quad (2)$$

where $\dot{Q}_{rej,PM}$ is the rejected heat rate requirements to ensure the performance of the thermodynamic power cycle.

The cooling effect ($\dot{Q}_{cooling}$) depends on the supplied heat rate source to the chiller ($\dot{Q}_{act,TAC}$) and its COP:

$$\dot{Q}_{cooling} = \dot{Q}_{act,TAC} \cdot COP_{TAC} \quad (3)$$

Finally, the nominal heat rate of the burner can be estimated as

$$\dot{Q}_{burner} = \dot{Q}_{act,PM} + \dot{Q}_{extra} \quad (4)$$

and its fuel consumption is computed as

$$\dot{F} = \frac{\dot{Q}_{burner}}{\eta_{burner}} \quad (5)$$

where η_{burner} is the biomass burner thermal efficiency.

3.2. Configuration description and characterization of the system components

Depending on the technologies presented in the first section of this work, the general scheme proposed in Fig. 1 represents six different possible configurations:

- ORC with low temperature working fluids, such as low boiling point hydrocarbons, integrated with adsorption or absorption cooling. Configurations 1 (ORC_{lowT} + ADS) and 2 (ORC_{lowT} + ABS).
- ORC with high temperature working fluids, such as siloxanes, integrated with adsorption or absorption cooling. Configurations 3 (ORC_{highT} + ADS) and 4 (ORC_{highT} + ABS).
- SE integrated with adsorption or absorption cooling. Configurations 5 (SE + ADS) and 6 (SE + ABS).

The main parameters of the model are depicted in Table 4, which presents average values according to the state of the art review.

The inlet flow cooling temperature of the prime mover has different values depending on the technology. In the case of ORC_{lowT}, this temperature is a bound variable in the range of 25–35 °C, so the aim of the parameter analysis is to evaluate the performance of the system when varying this temperature in the specified range. Consequently, the electric efficiency of the ORC will suffer

[1] All the heat rates and power detailed in the model description are expressed as absolute values.

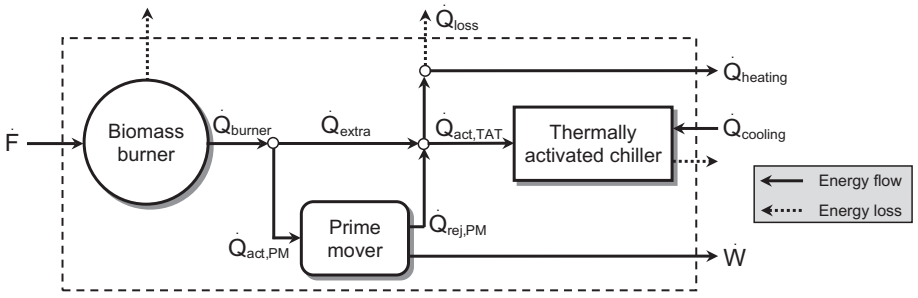

Fig. 1. Schematic description of the CCHP model.

Table 4
Input parameters used in the CCHP model.

Subsystem	Parameter		Units	Value
Burner	Efficiency, η_{burner}		%	85
Power (prime mover)	Efficiency, η_{PM}	ORC_{highT}	%	18
		ORC_{lowT}	%	12[a]
		SE	%	25
	$\Delta T_{ref,PM}$		°C	20
Cooling (TAC)	Coefficient of performance, COP_{TAC}	ADS	–	0.6
		ABS	–	0.7
	Activation temperature	ADS	°C	70
		ABS	°C	90

[a] Nominal value (variation caused by the increase in cooling temperature according to the Carnot factor and confirmed by technical documentation.

a significant variation which has been taken into account according to the Carnot factor [18] and confirmed by the efficiency variation provided by some manufacturers. On the contrary, the ORC_{highT} and the SE inlet flow cooling temperature is 60 °C, which is the characteristic inlet heat sink temperature value of the CHP units.

4. Evaluation methodology

Many evaluation criteria have been formulated to quantify the benefits achieved by the use of CHP, CCHP, or polygeneration plants compared with separated generation. Some well-known parameters are the *Energy Utilization Factor* (EUF), the *Artificial Thermal Efficiency* (ATE), the *Primary Energy Saving Ratio* (PESR), the *Exergy Efficiency* (ψ), or the *Greenhouse Gases Emission Reduction Potential* (ΔGHG). All these criteria are usually calculated considering only the nominal parameters and they do not consider partial load operation or plant management [53,58].

In order to assess the proposed CCHP configurations, both the ATE and the PESR have been selected due to their influence in several national policies to support efficient plants [58]. These parameters are used to compare multiproduct systems against reference plants with the same energy products ($\dot{W}, \dot{Q}_{cooling}$, and $\dot{Q}_{heating}$) in terms of energy efficiency and primary energy savings, as Fig. 2 depicts.

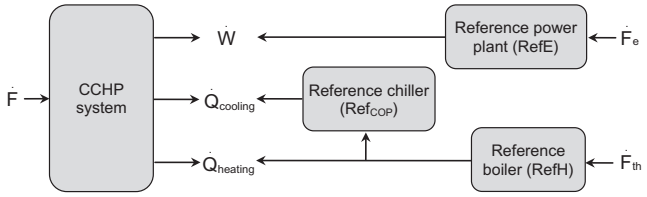

Fig. 2. Comparison framework for ATE and PESR calculation.

Table 5
Input parameters of the reference system.

Parameter	Units	Value	Source
Reference power plant efficiency, RefE	%	25	[59]
Reference boiler efficiency, RefH	%	86	
Reference chiller coefficient of performance (double effect LiBr–water), Ref_{COP}	–	1.4	–

RefH and RefE are the characteristic efficiencies of the reference subsystems defined by Directive 2004/8/EC [59] for combined electricity and heat production. On the other hand, due to the lack of a reference system for the cooling generation, there are two choices: a high performance vapor-compression chiller (COP ≈ 4), consuming electricity from the reference power plant, or a double effect absorption chiller (COP ≈ 1.4), consuming heat from the reference boiler. The second case has been selected due to its lower primary energy consumption in order to have a more realistic comparison framework. The selection of a vapor-compression chiller as a reference system would have entailed better results for the CCHP system, in terms of primary energy savings.

All these efficiencies are presented in Table 5, where it can be seen the values of the reference parameters that were finally taken into account in the present work.

Hence, based on this schematic comparison framework defined in Fig. 2, the ATE parameter is calculated with the following equation [53]:

$$ATE = \frac{\dot{W}}{\dot{F} - \frac{\dot{Q}_{heating}}{RefH} - \frac{\dot{Q}_{cooling}}{RefH \cdot Ref_{COP}}} \quad (6)$$

The ATE can also be expressed depending on the Primary Energy Saving Ratio [53], which is the amount of saved energy represented by the difference between two terms: the fuel consumed in a stand-alone system and that consumed in a CCHP scheme ($\dot{F}_e + \dot{F}_{th}$ and $\dot{F}$, respectively, in Fig. 2).

$$ATE = \frac{1}{\frac{1}{RefE} + \frac{PESR}{\eta_{PM}(1 - PESR)}} \quad (7)$$

Thus, according to Eq. (7), the minimum value of the ATE (ATE_{min}) required to achieve a positive PESR is equal to the considered reference power plant efficiency value (RefE), which in this case is 25%, as shown in Table 5.

5. Results and discussion

5.1. Results analysis

The evaluation of the ATE has been carried out through a so-called *cooling factor* (C), specifically defined to facilitate the analy-

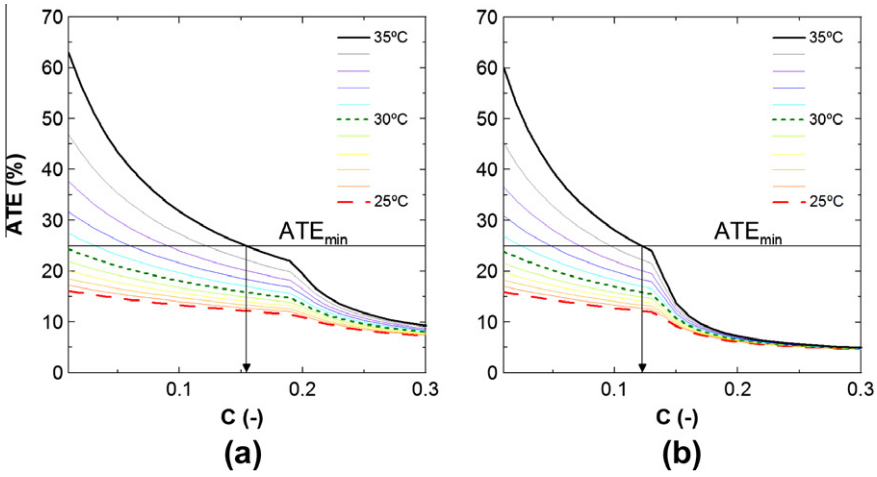

Fig. 3. ATE results for the proposed configurations depending on the cooling factor (C) and the inlet flow cooling temperature of the ORC: (a) Configuration 1 (ORC_{lowT} + ADS). (b) Configuration 2 (ORC_{lowT} + ABS).

sis, and the prime mover heat sink temperature in the case of ORC_{lowT} only (configurations 1 and 2).

The cooling factor is defined as

$$C = \frac{\dot{Q}_{cooling}}{\dot{Q}_{cooling} + \dot{Q}_{heating}} \quad (8)$$

According to Eq. (8), low C values represent high production of heating ($\dot{Q}_{heating}$) in comparison to cooling ($\dot{Q}_{cooling}$). This parameter has been proposed in order to evaluate the relation between the generated heating and cooling loads to achieve a minimum ATE value.

Figs. 3 and 4 show the results of the parameter analysis based on the state of the art review and on the model detailed in Section 3. As expected from previous works, a rise in the C parameter implies a decrease in the ATE, and, consequently, in the PES of the CCHP plant. This means that the higher is the cooling-to-heating generation ratio, the lower energy savings will be achieved by the plant operation. However, some of the proposed configurations are more sensitive to variation in C than others. On the one hand, configurations 3 and 5, where the rejected heat from the prime mover is used directly ($T_{ref,PM} \geqslant T_{act,TAC}$), allow PES to be achieved at higher C values. This is caused by the lack of the extra heat

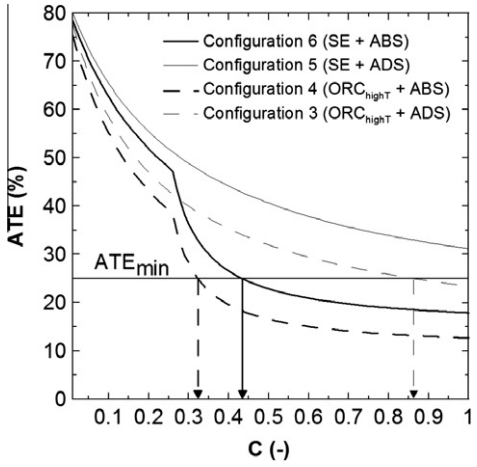

Fig. 4. ATE results for the configuration 3 (ORC_{highT} + ADS), 4 (ORC_{highT} + ABS), 5 (SE + ADS) and 6 (SE + ABS) depending on the cooling factor (C).

($\dot{Q}_{extra}$) from the biomass burner required to achieve the necessary heat source temperature of the TAC. On the other hand, configurations requiring extra heat from the flue gases to achieve the chiller activation temperature are more severely penalized in their ATE and PES performance by the rise in C. This is prompted by the contribution of extra heat, which is required to raise the temperature of the PM cooling flow but is not entirely used afterwards for heating or cooling purposes, causing an increment in the negative slope of the ATE curve. In other words, heat losses are required to ensure the proper operation of the CCHP plant and this aspect is reflected in the pronounced decrease of the ATE curve. These results condition the C limit value to achieve primary energy savings in comparison with the reference system.

It is also important to remark that the configurations integrated by the SE, which has the highest electrical efficiency among the considered PMs, achieve the best PES performance when the cooling load is relatively low ($C \sim 0.25$) in comparison to the heating generated. However, as was stated before, the rise in the cooling factor implies that direct coupling of PM and TAC units is more important for achieving primary energy savings than high electrical efficiency of the PM. So, the rise in C improves the performance of configuration 3 (ORC_{highT} + ADS) in comparison to configuration 6 (SE + ABS), despite the higher efficiency and COP of the SE and the absorption chiller, respectively.

In summary, the order of the configurations according to their flexibility, which can be defined as the ease of generating cooling in comparison to heating while continuing to achieve PES in the process, is:

1. Configuration 5 (SE + ADS).
2. Configuration 3 (ORC_{highT} + ADS): C ≈ 0.86.
3. Configuration 6 (SE + ABS): C ≈ 0.43.
4. Configuration 4 (ORC_{highT} + ABS): C ≈ 0.32.
5. Configuration 1 (ORC_{lowT} + ADS): C ≈ 0.16.
6. Configuration 2 (ORC_{lowT} + ABS): C ≈ 0.12.

Despite the high cooling factor limits of configurations 3–6, the long-term problems of SE when they operate with biomass resources and the scarcity of ORC_{highT} units in the power range below 200 kW_e limit their use in small-scale CCHP plants.

Configurations integrated by the ORC_{lowT} present the lowest cooling factor limits to achieve PES, as was expected due to the lower efficiency and low heat sink temperatures. In fact, with the current nominal performance of commercial ORC units with low

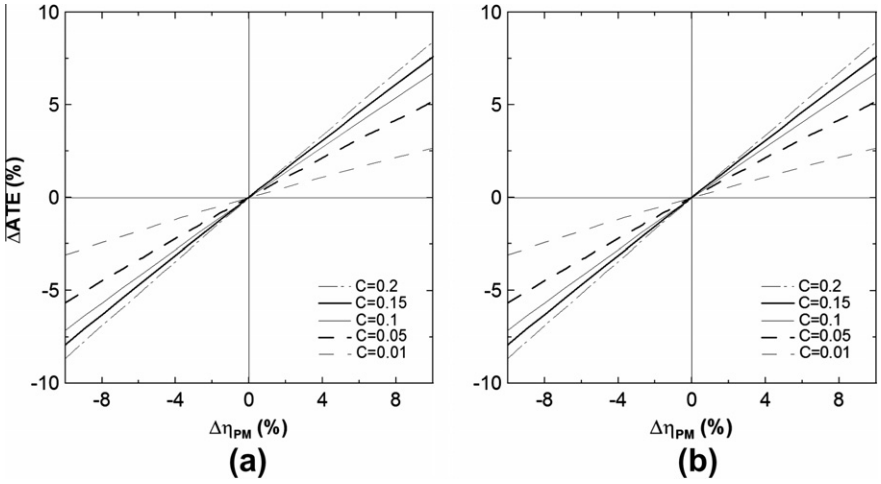

Fig. 5. ATE variation depending on the ORC_{lowT} electric efficiency variation: (a) Configuration 1 (ORC_{lowT} + ADS). (b) Configuration 2 (ORC_{lowT} + ABS).

boiling point hydrocarbons as their working fluid (inlet cooling temperature of 25 °C), integration with thermally activated cooling technologies in a CCHP plant is not feasible in an energy efficient way. However, a slight rise in the cooling temperature (30–35 °C) will allow primary energy savings and would increase the applications of these technologies to CCHP systems based on biomass combustion and other renewable energy sources. In addition, this type of ORC would offer a significant potential due to its residential and commercial field of application and its current market availability, but the development of new commercial units with higher source and sink temperatures would favor its integration in CCHP plants with higher *C* values.

5.2. Sensitivity analysis

A sensitivity analysis was carried out to assess the energy efficiency behavior of configurations 1 and 2 when the main parameters of every subsystem involved (η_{PM}, COP_{TAC} and η_{burner}) were varied.

Figs. 5–7 show the results of the sensitivity analysis. A ±10% variation in the electrical efficiency of the PM gives a low variation in ATE. In addition, the influence of the variation in the chiller's COP is also small in low *C* ranges, but this variation has a peak influence with the *C* values between 0.15 and 0.2, where the ±10% ΔCOP gives a significant ΔATE. However, the rise in the plant cooling factor softens this effect. Finally, the most relevant factor in terms of its influence on the ATE is the burner efficiency, which might give variations from −60% up to 100% when its nominal value is modified by ±10%. However, the rise in the *C* parameter mitigates this effect. It should be noted that the biomass burner efficiency can be severely influenced by the fouling, slagging, and ash agglomeration processes; thus, these phenomena may define the plant viability in terms of PES.

In summary, ATE is highly sensitive to the burner efficiency and less sensitive to the electrical efficiency of the prime mover and the coefficient of performance of the thermally activated cooling unit. Therefore, attention should be paid to maintaining the nominal burner efficiency by avoiding the phenomena that lower its value.

5.3. Other considerations

Besides the thermodynamic integration based on the nominal operation parameters of every subsystem involved in the CCHP systems analyzed and its overall energy efficiency, it is very important to take into account other considerations when designing this type of plant. Even though it is not the aim of the present work, the authors have identified two main aspects that should also be considered: the O&M and the economic constraints, which are

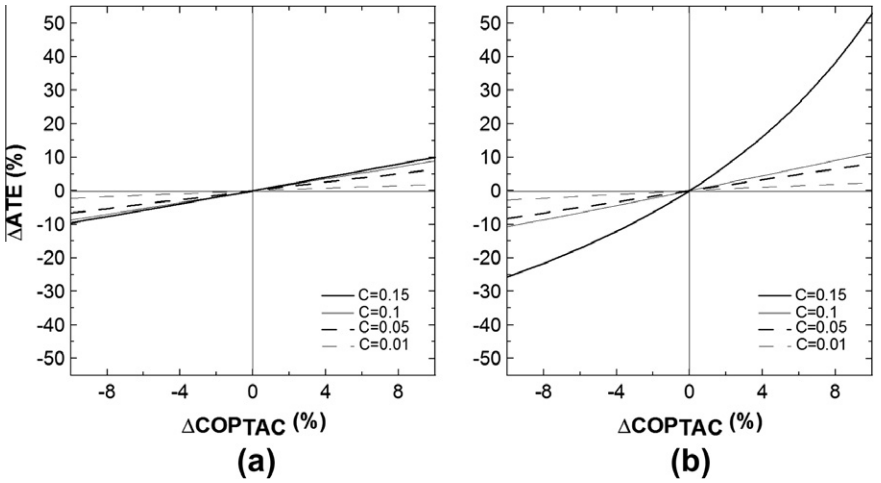

Fig. 6. ATE variation depending on the TAC unit coefficient of performance variation: (a) Configuration 1 (ORC_{lowT} + ADS). (b) Configuration 2 (ORC_{lowT} + ABS).

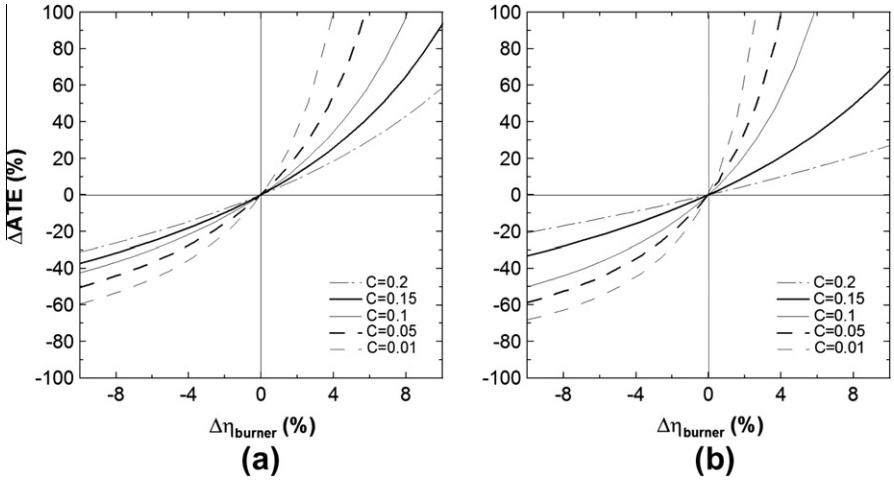

Fig. 7. ATE variation depending on the biomass burner efficiency variation: (a) Configuration 1 (ORC_{lowT} + ADS). (b) Configuration 2 (ORC_{lowT} + ABS).

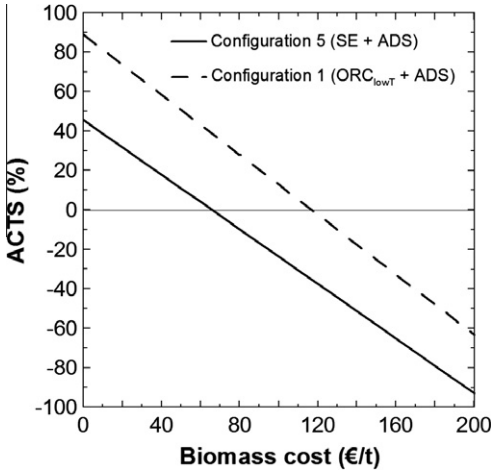

Fig. 8. ATCS results comparison between configuration 1 (ORC_{lowT} + ADS) and configuration 5 (SE + ADS).

analyzed in a preliminary way in order to complete the point of view of the work.

With regards to the operational problems that might appear, CCHP configurations integrated by SE are the most troublesome due to the higher heat source temperatures required for its correct operation. These temperatures might cause ash related effects when working with some types of solid biomass. Hence, configurations integrated by ORC (whether driven by flue gases or an intermediate fluid) are more adequate to avoid O&M problems when working with high ash content biofuels.

From an economic point of view, SEs entail a higher investment cost than ORCs. This difference is responsible for the higher long-term economic viability of the plant configurations integrated by ORC. As a preliminary assessment, Fig. 8 depicts the difference in the annual total cost savings (ATCSs), defined by the ratio of the annual cost saving of the CCHP system in comparison with the annual cost of the stand-alone system, between configurations 5 and 1. This preliminary analysis was developed using the methodology described by Jiang-Jiang et al. [60], under average cost considerations from Tables 1–3, a cooling factor of 0.1 and respective reference electricity and gas prices of 0.08 and 0.05 €/kW h.

According to the above mentioned O&M and economic constraints, low temperature organic Rankine cycles gain importance in comparison to Stirling engines, despite the higher energy efficiency results of the latter, when integrating them in CCHP plants based on biomass combustion.

6. Conclusions

The main objective of this work was to review the technologies involved in CCHP plants based on solid biomass combustion and to evaluate their performance in terms of PES in comparison to stand-alone conventional systems when integrated with supply cooling and low grade heating demands.

These types of systems are already operating but not every available technology is present in existing plants (only ORC_{highT} integrated with absorption refrigeration is a widespread configuration). Therefore special emphasis was put on analyzing the behavior of the plants involving small-scale ORCs, since this technology is strongly present in the market (unlike SEs), and CCHP plants with net power outputs up to 200 kW_e (non-existent units in the market for ORC_{highT}) present a high potential in residential, commercial, and institutional buildings.

As demonstrated in this work, small-scale CCHP based on biomass combustion can be developed with the currently available ORC technology in an energy efficient way. However, the integration of this technology with absorption or adsorption refrigeration is limited to plants where the heating requirement is very high in comparison to the cooling demands ($C \approx 0.1$) and the heat sink temperature of the ORC is high (30–35 °C) within the range of nominal values provided by the manufacturers (20–35 °C).

As a result, ORCs with low boiling point hydrocarbons as the working fluid are a very promising alternative for integration in biomass fuelled CCHP plants, not only from the point of view of energy efficiency and market availability, but also when taking into consideration other aspects such as O&M constraints or economic performance. Nevertheless, a slight increase in their sink temperatures will lead to higher primary energy savings. Further work to develop small-scale commercial ORC units with higher source and sink temperatures will improve their application, since higher cooling loads could be achieved, in comparison to heating, while still attaining energy savings.

Furthermore, it is important to note that configurations integrated by technologies which are directly coupled according to their heat sink and source temperatures achieve a better PES performance when varying the relation between the cooling and heating loads, in terms of CCHP plant steady-state design specifications.

The abovementioned conclusions favor the development of biomass fuelled CCHP plants, which might increase the potential use of this renewable source in countries or areas where it has not yet reached expected levels.

Acknowledgements

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